Suppression of heavy quarks in heavy ion collisions

Che-Ming Ko
Texas A&M University

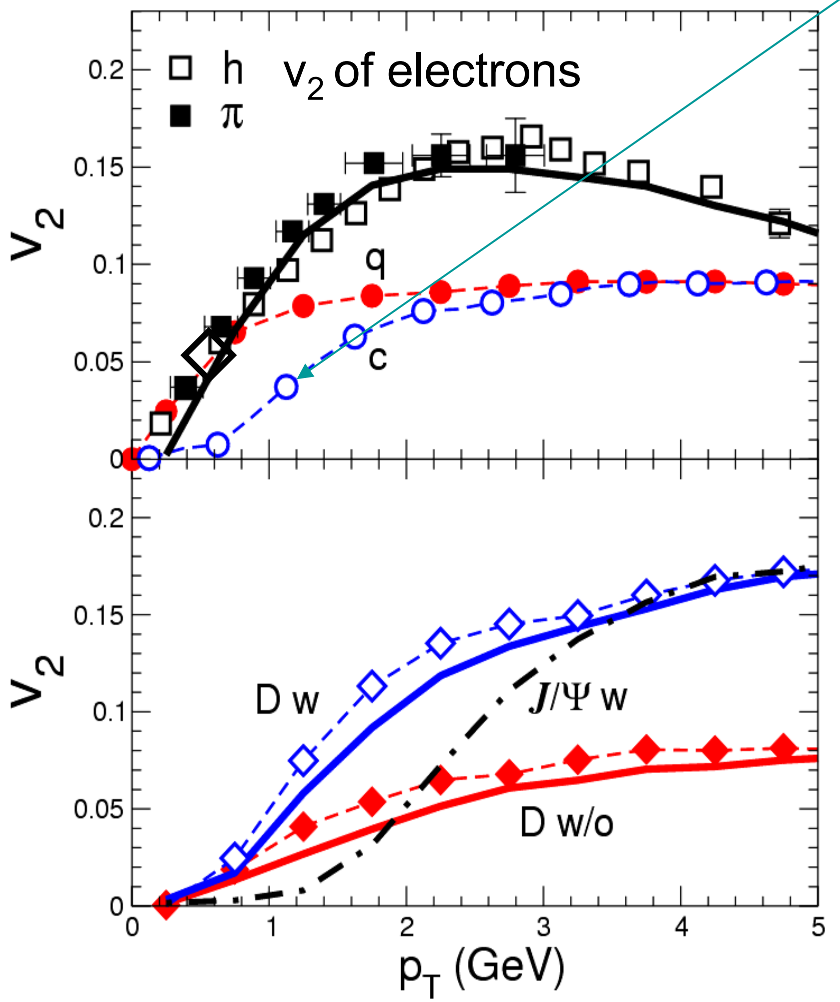
- Introduction
- Heavy quark scattering (three-body scattering)
- Heavy quark drag coefficients
- Heavy quark momentum degradation
- Nuclear modification factor for heavy quarks
- Summary

Collaborator: Wei Liu (Texas A&M University)

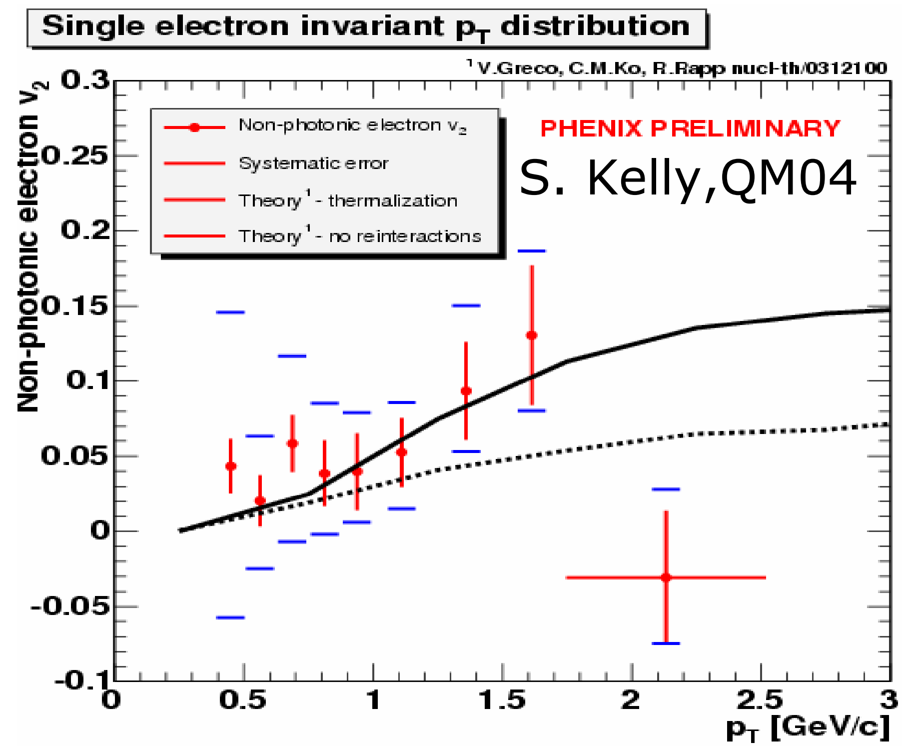
Charmed meson elliptic flow

Greco, Rapp, Ko, PLB595, 202 (04)

Quark coalescence

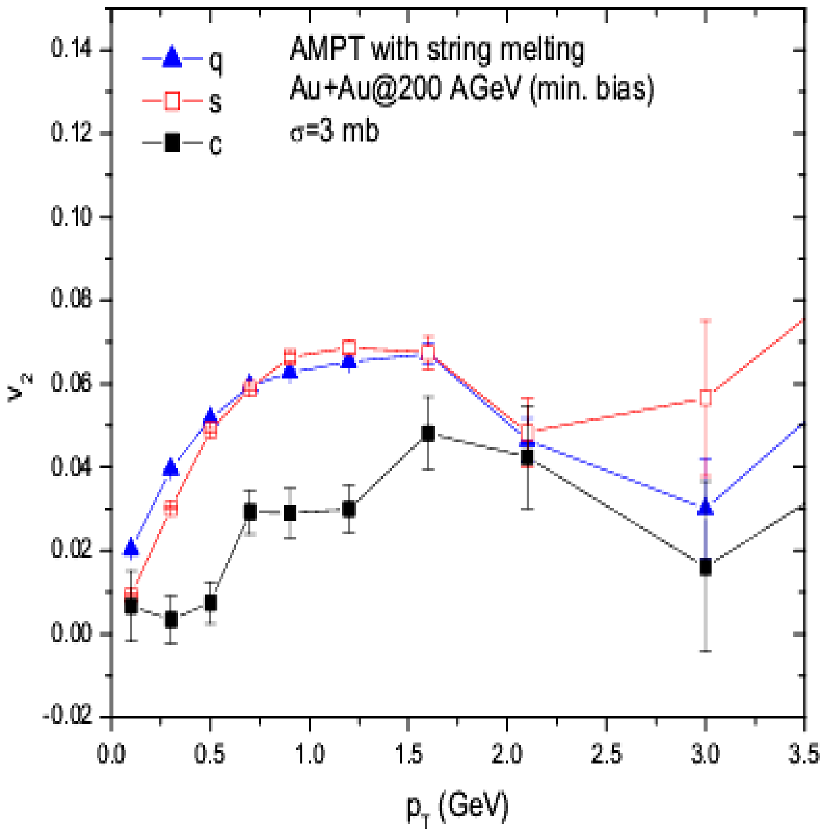


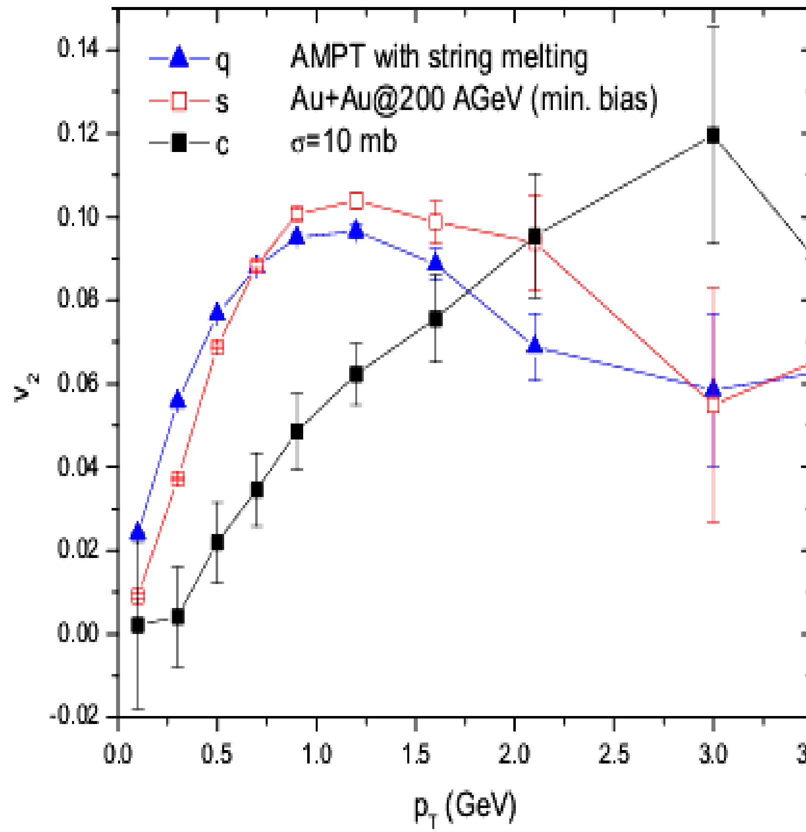
Smaller charm v_2 than light quark v_2 at low p_T due to mass effect



Data consistent with thermalized charm quark with same v_2 as light quarks

Charm quark elliptic flow from AMPT

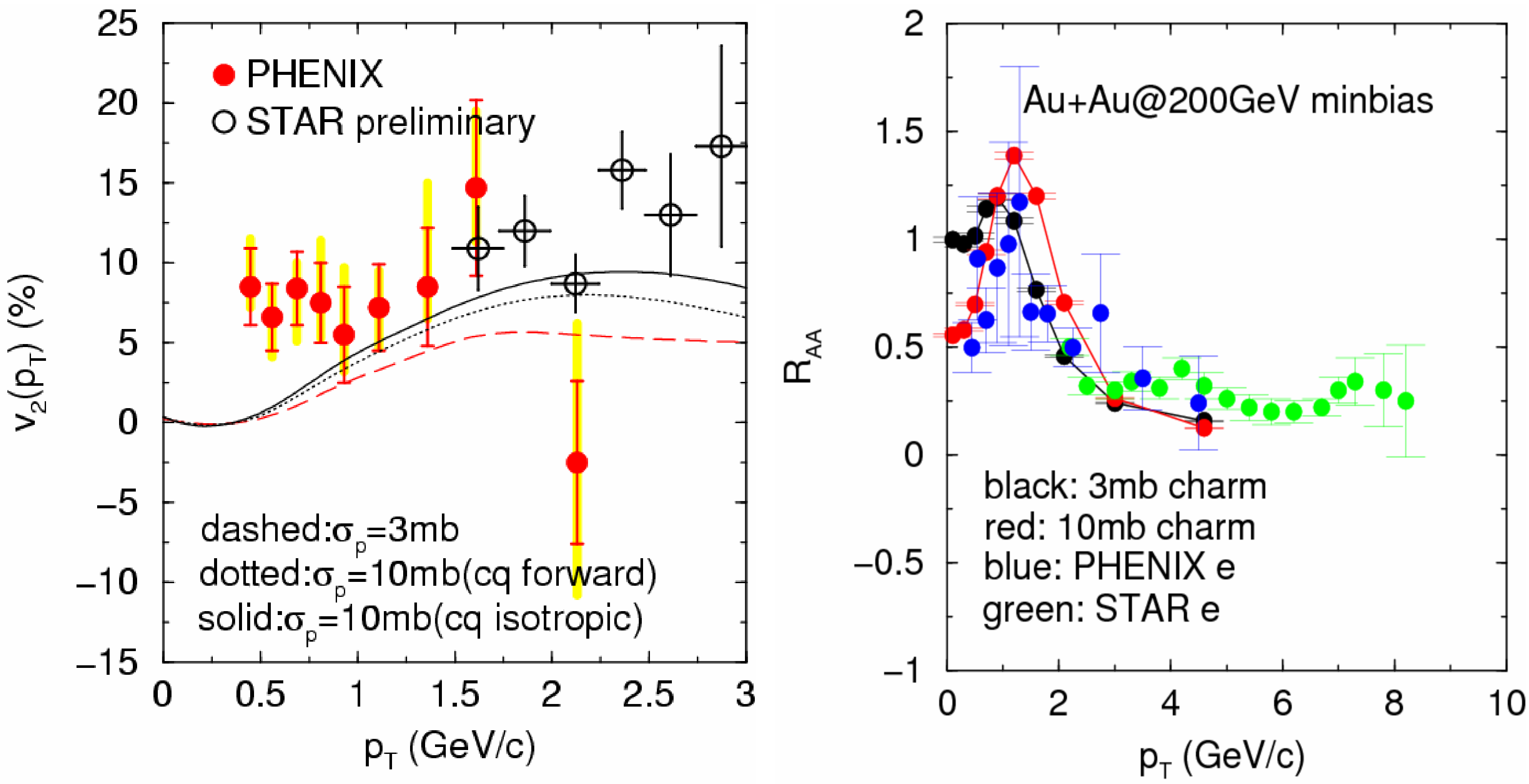




- P_T dependence of charm quark v_2 is different from that of light quarks.
- At high p_T, charm quark has similar v_2 as light quarks.
- Charm elliptic flow is also sensitive to parton cross sections

Charm R_{AA} and elliptic flow from AMPT

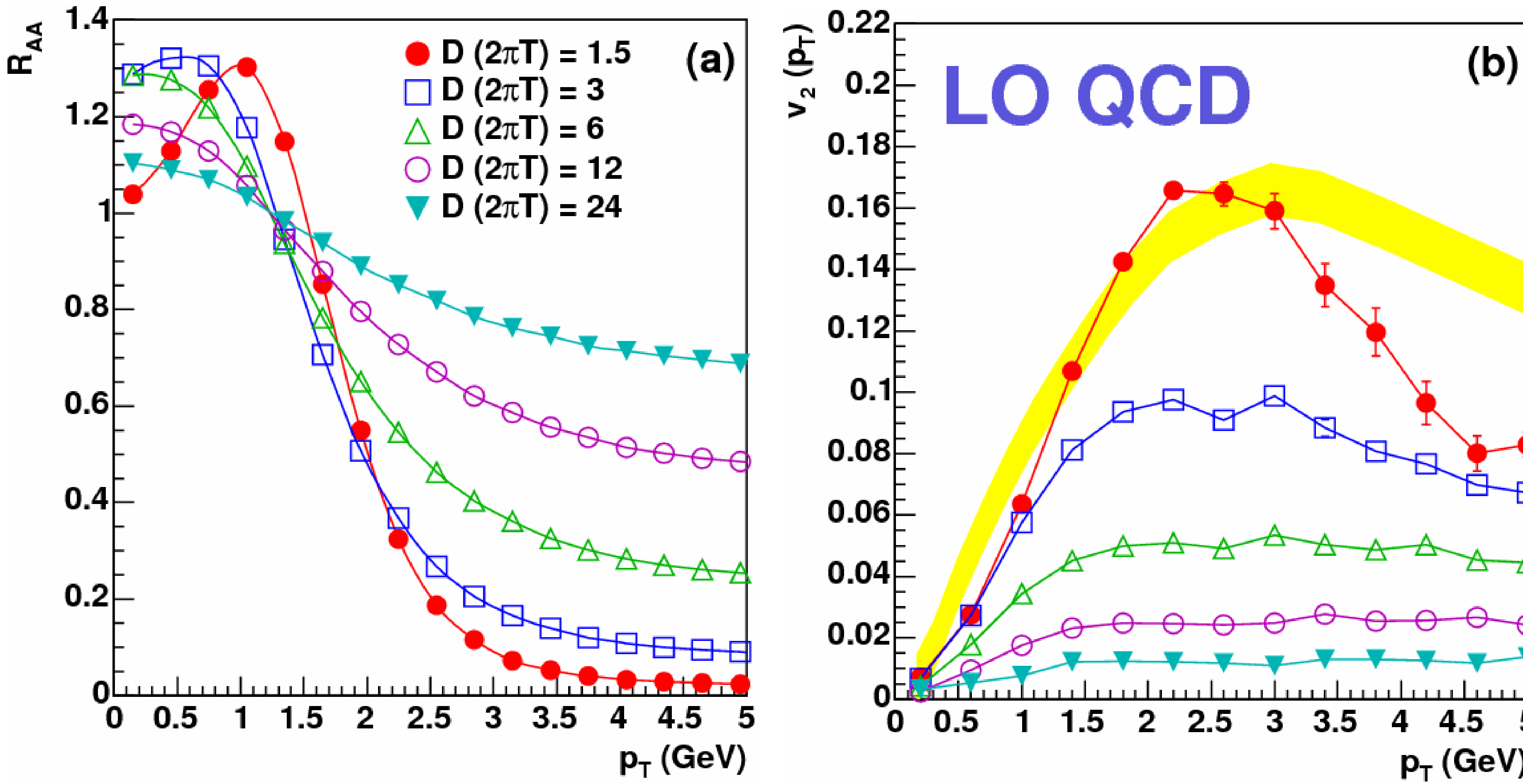
Zhang, Chen & Ko, PRC 72, 024906 (05)



- Need large charm scattering cross section to explain data.
- Smaller charmed meson elliptic flow is due to use of current light quark masses.

Charm elliptic flow from the Langevin model

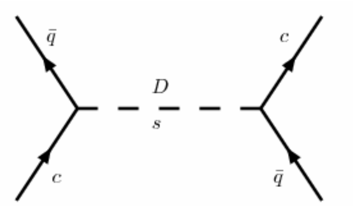
Moore & Teaney, PRC 71, 064904 (2005)



pQCD gives D≈a/(2πT) in QGP with a=6

Possible origin of large charm scattering cross section

- Resonance scattering (van Hees, Greco & Rapp, PRC 73, 034913 (06))



$$\boxed{\sigma_{c\bar{q}\to c\bar{q}} = \frac{1}{9}\,\frac{2J+1}{4}\,\frac{\pi}{k^2}\,\frac{\Gamma_D^2}{\left(s^{1/2} - m_D\right)^2 + \Gamma_D^2/4}}$$

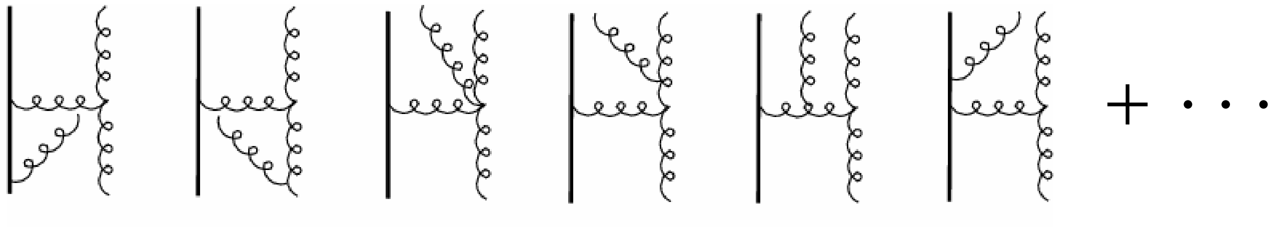
With $m_c \approx 1.5$ GeV, $m_q \approx 5$-10 MeV, $m_D \approx 2$ GeV, $\Gamma_D \approx 0.3$-0.5 GeV, and including scalar, pseudoscalar, vector, and axial vector D mesons gives

$$\boxed{\sigma_{cq\to cq}(s_{1/2}=m_D) \approx 6 \text{ mb}}$$

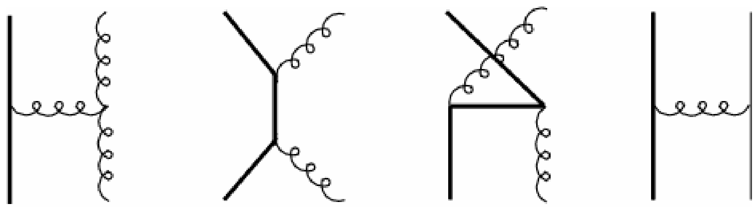
Since the cross section is isotropic, the transport cross section is 6 mb, which is about 4 times larger than that due to pQCD t-channel diagrams. However, LQCD seems not to support heavy-light bound states in QGP (Talk by Karsch).

Heavy quark energy loss in pQCD

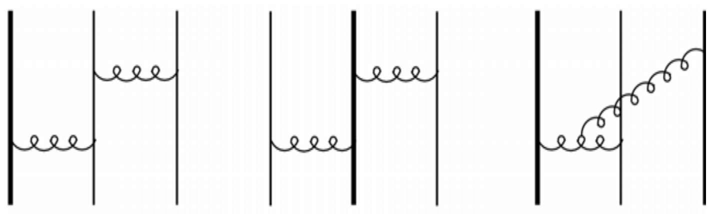
a) Radiative energy loss (Amesto *et al.*, hep-ph/0511257)



b) Radiative and elastic energy loss (Wicks *et al.*, nucl-th/0512076)

a) + 

c) Three-body elastic scattering (Liu & Ko, nucl-th/0603004)

a) +b) +  + · · ·

May be important as interparton distance ~ range of parton interaction
At T=300 MeV, N_g~(N_q+N_{qbar})~ 5/fm^3, so interparton distance ~ 0.3 fm
Screening mass m_D=gT~600 MeV, so range of parton interaction ~ 0.3 fm

Fokker-Planck equation

$$\frac{\partial f(p,t)}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(p) + \frac{\partial}{\partial p_j} B_{ij}(p)\right] f(p,t)$$

F(p,t): heavy quark momentum distribution

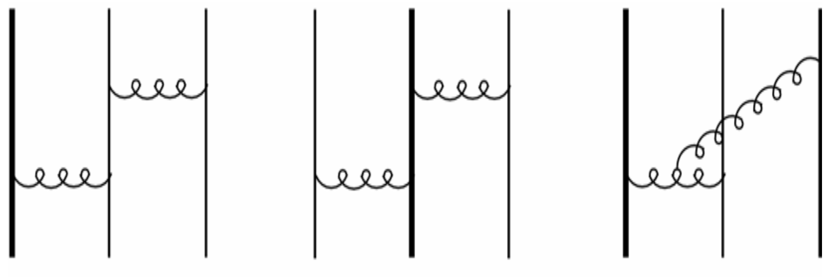
$$A_i(p) = p_i \gamma(|\mathbf{p}|),\;\; B_{ij}(p) = \left(\delta_{ij} - \frac{p_i p_j}{|\mathbf{p}|^2}\right) B_0(|\mathbf{p}|) + \frac{p_i p_j}{|\mathbf{p}|^2} B_1(|\mathbf{p}|)$$

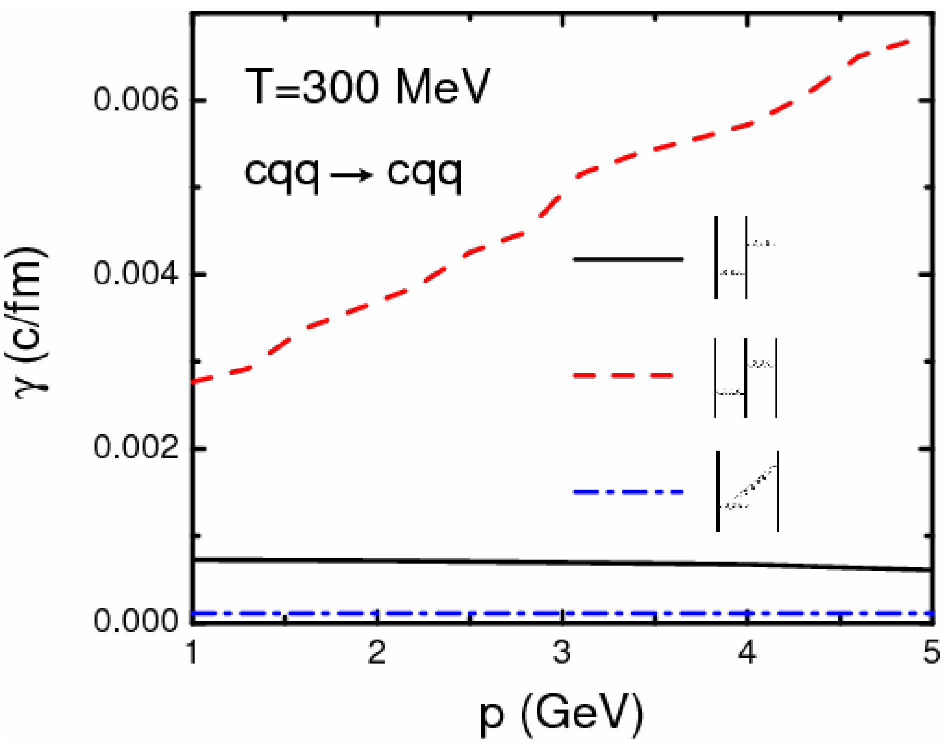
$$\text{Drag coefficient } \gamma(|\mathbf{p}|) = \langle 1 \rangle - \frac{\langle \mathbf{p}\cdot\mathbf{p}' \rangle}{|\mathbf{p}|^2}$$

$$\text{Diffusion coefficient } B_0(|\mathbf{p}|) = \frac{1}{4}\left[\langle |\mathbf{p}|^2 \rangle - \frac{\langle (\mathbf{p}\cdot\mathbf{p}')^2 \rangle}{|\mathbf{p}|^2}\right]$$

$$\langle X(p_{j_1}) \rangle = \frac{1}{2E_{i_1}} \frac{1}{\gamma_{i_1}} \prod_{k=2,\dots,m} \int \frac{g_{i_k} d^3 p_{i_k}}{(2\pi)^3 2E_{i_k}} \prod_{l=1,\dots,n} \int \frac{d^3 p_{j_l}}{(2\pi)^3 2E_{j_l}} \prod_{k=2,\dots,m} f(p_{i_k}) \prod_{l=2,\dots,n} 1 \pm f(p_{j_l})$$
$$\times \overline{|M_{i_1 \dots i_m \to j_1 \dots j_n}|^2} (2\pi)^4 \delta^{(4)}\left(\sum_{k=1,\dots,m} p_{i_k} - \sum_{l=1,,\dots,n} p_{j_l}\right) X(p_{j_1})$$

1) $Qqq \to Qqq$, $Qq\bar{q} \to Qq\bar{q}$, $Q\bar{q}\bar{q} \to Q\bar{q}\bar{q}$ with different flavors (6 diagrams)





True 3-body interaction requires intermediate quark to be off shell, achieved by taking the real part of its propagator after including its collisional width

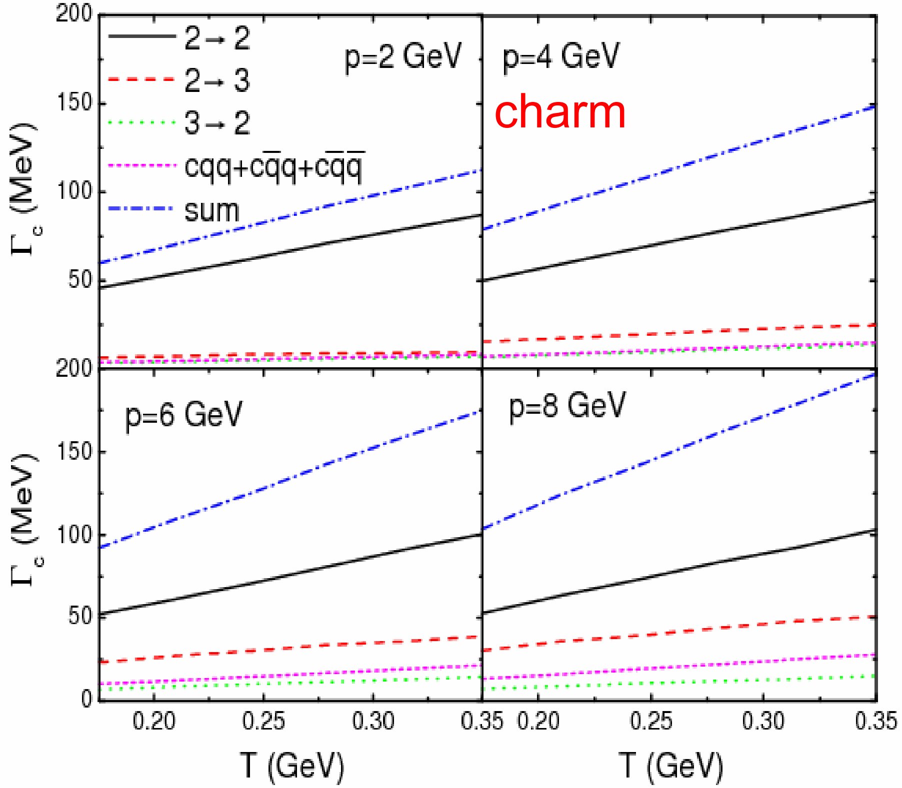
$$m_{Q,q} \to m_{Q,q} + i\frac{\Gamma_{Q,q}}{2}$$

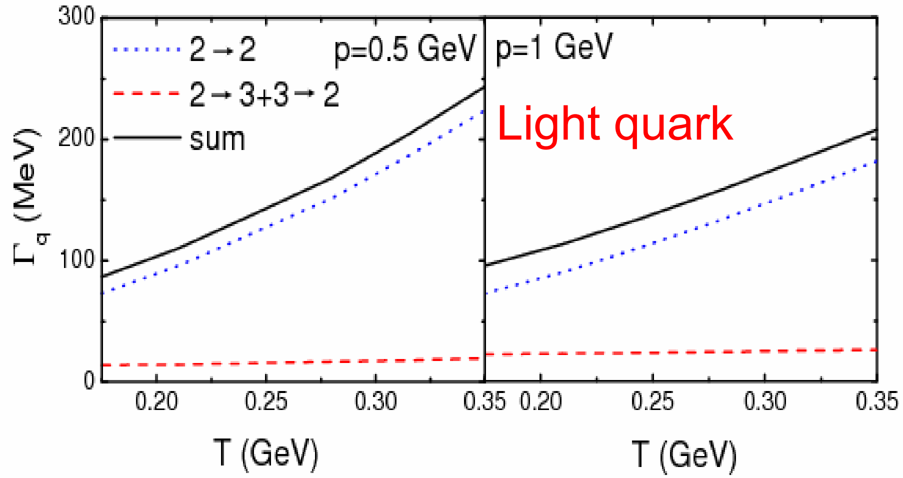
Screening mass $m_D = gT$

Thermal mass $m_g = \sqrt{3} m_q = \frac{m_D}{\sqrt{2}}$

Dominated by diagram with two gluons attached to heavy quark. Not surprising as other diagrams can be considered as medium modification of light quarks and gluons.

Collisional width of quarks in QGP





$$\Gamma_{Q,q} = \hbar \sum_i \left\langle \overline{\left|M_i\right|^2} \right\rangle$$

$$\left\langle \overline{\left|M_{i_1\cdots i_m\to j_1\cdots j_n}\right|^2} \right\rangle = \frac{1}{2E_{i_1}} \prod_{k=2,\cdots,m} \int \frac{g_{i_k} d^3p_{i_k}}{(2\pi)^3\, 2E_{i_k}} \prod_{l=1,\cdots,n} \int \frac{d^3p_{j_l}}{(2\pi)^3\, 2E_{j_l}}$$

$$\times \prod_{k=2,\cdots,m} f(p_{i_k}) \prod_{l=2,\cdots,n} 1 \pm f(p_{j_l}) \overline{\left|M_{i_1\cdots i_m\to j_1\cdots j_n}\right|^2}$$

$$\times (2\pi)^4 \delta^{(4)}\left(\sum_{k=1,\cdots,m} p_{i_k} - \sum_{l=1,\cdots,n} p_{j_l} \right)$$

With $\alpha_s = g^2/4\pi = 0.3$, quark collisional widths are mainly due to 2-body elastic scattering. Width of bottom quark is about two thirds of that of charm quark.

2) $Qqq \rightarrow Qqq$, $Q\overline{qq} \rightarrow Q\overline{qq}$ with same flavor

6 extra diagrams due to interchange of final two light quarks. Give same contribution as that due to direct diagrams. Interference terms are two orders of magnitude smaller.

3) $Qq\bar{q} \rightarrow Qq\bar{q}$ with same flavor

5 extra diagrams from exchanging a gluon between heavy quark and light quark, antiquark, or gluon in quark and antiquark annihilation. Contribution is two order of magnitude smaller than that due to direct diagrams.

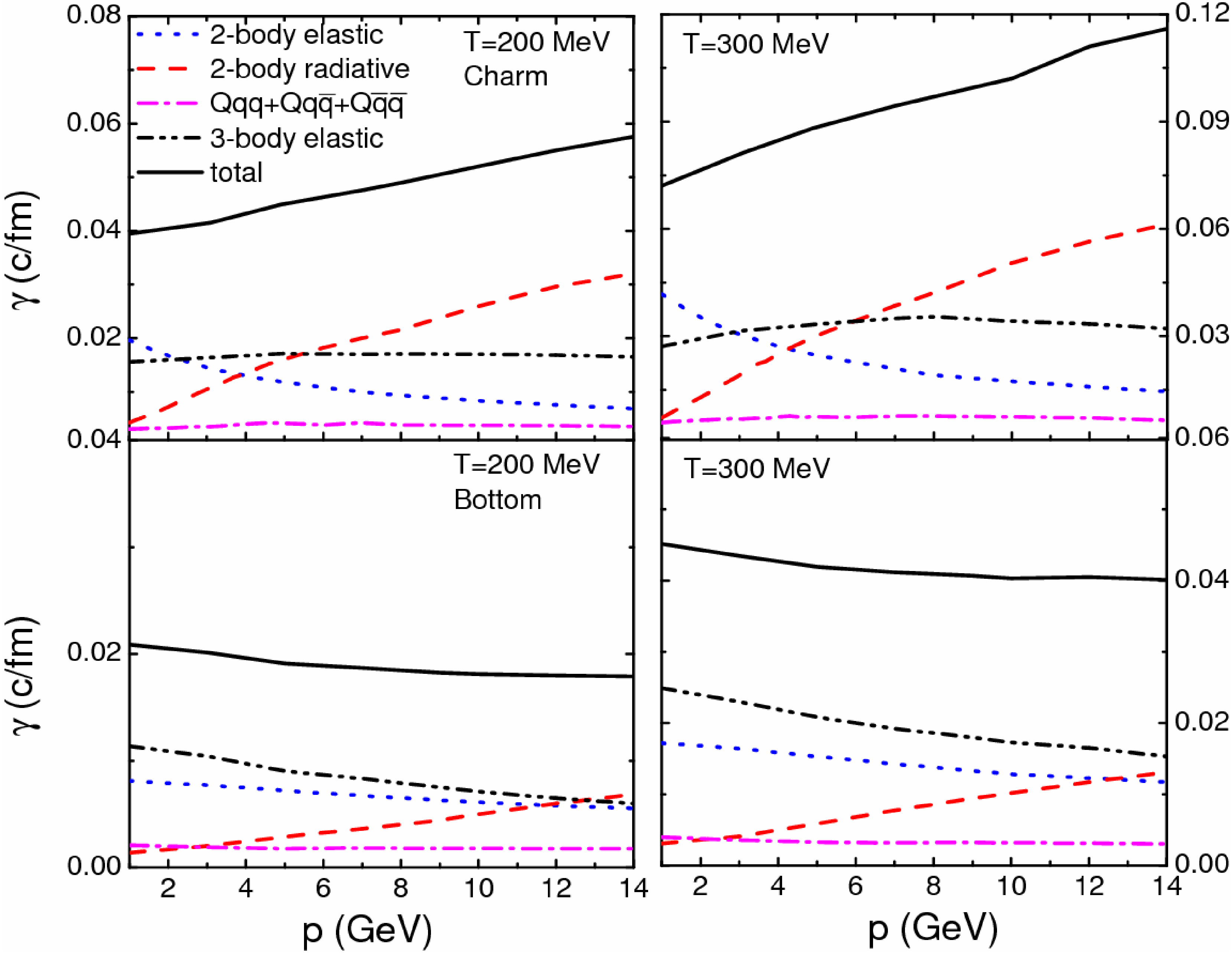
4) $Qqg \rightarrow Qqg$ and $Q\bar{q}g \rightarrow Q\bar{q}g$

36 diagrams obtained by attaching an extra gluon to all parton lines and three-gluon vertices in Qq→Qqg. Only two diagrams with two gluons attached to heavy quark have been evaluated.

5) $Qgg \rightarrow Qgg$

123 diagrams obtained from Qg→Qgg by attaching an extra gluon. Only two diagrams with two gluons attached to heavy quark have been calculated.

Heavy quark drag coefficients in QGP



Heavy quark Momentum degradation in QGP

Fokker-Planck equation → $$\boxed{\frac{d\langle p_T\rangle}{dt}=-\langle\gamma(p_T,T)p_T\rangle}$$

Using $$\boxed{\gamma(p_T,T)\approx\gamma_0(T)(1+ap_T),\quad \langle p_T^2\rangle\approx\langle p_T\rangle^2}$$

then $$\boxed{\langle p_T\rangle=\frac{B}{1-aB}}$$ with $$\boxed{B=\frac{p_0\exp\left(-\int_{\tau_0}^{\tau_f}\gamma_0(\tau)d\tau\right)}{1+ap_0}}$$

τ_f : smaller of the time when QGP ends and the time when heavy quark escapes the expanding QGP fireball.

QGP fireball dynamics: $$\boxed{V(\tau)=\pi\tau[R_0+\tfrac{a}{2}(\tau-\tau_0)^2]}$$

$T(\tau)$ from entropy conservation

$R_0=7\ \text{fm},\ \tau_0=0.6\ \text{fm},\ a=0.1\ c^2/\text{fm}$

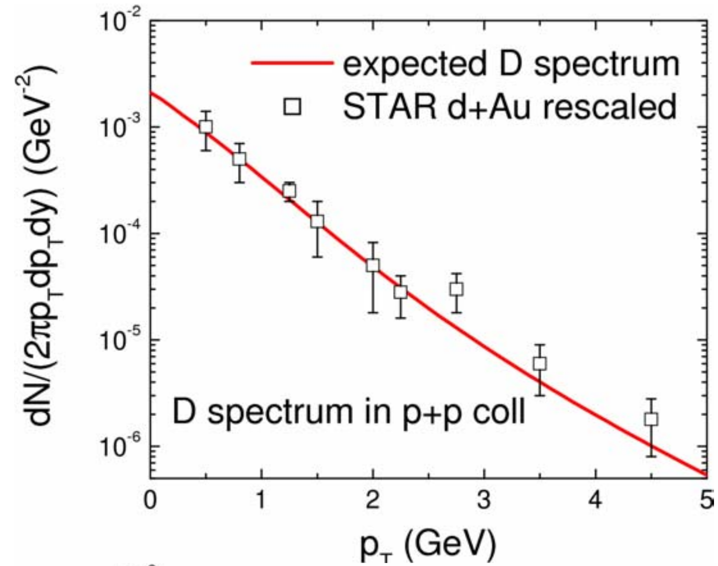
$T_i=350\ \text{MeV},\ T_c=175\ \text{MeV}\ @\ \tau_c=5\ \text{fm}$

Appropriate for central Au+Au @ 200 AGeV

Initial heavy quark spectra

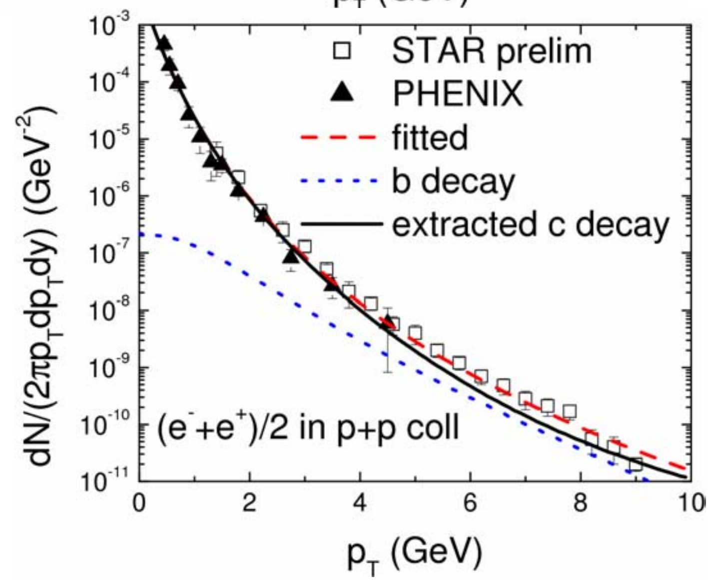
Charm quarks: from fitting simultaneously measured spectrum of charm mesons from d+Au collisions and of electrons from heavy meson decays in p+p collisions.

$$\frac{dN_c}{d^2p_T} = N_{coll}\frac{dN_c^{pp}}{d^2p_T}$$
$$= \frac{19.2\left[1+\left(\frac{p_T}{6}\right)^2\right]}{(1+p_T/3.7)^{12}\left[1+\exp(0.9-2p_T)\right]}$$

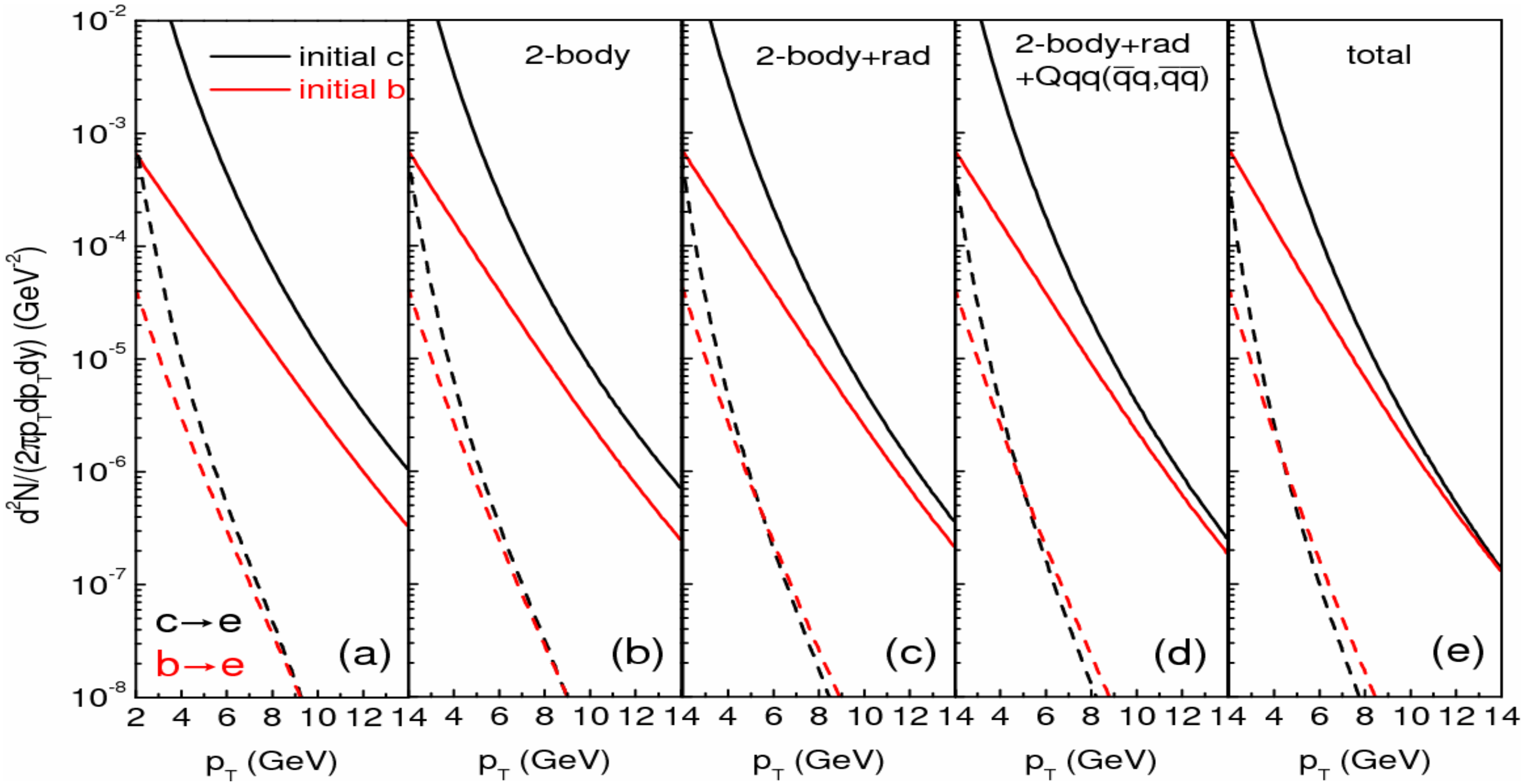


Bottom quarks: from the upper limit of uncertainty band of pQCD prediction

$$\frac{dN_b}{d^2p_T} = N_{coll}\frac{dN_b^{pp}}{d^2p_T}$$
$$= 0.0025\left[1+\left(\frac{p_T}{16}\right)^5\right]\exp\left(-\frac{p_T}{1.495}\right)$$



Heavy quark and decay electron spectra



Peterson fragmentation function is used to fragment heavy quarks to heavy mesons

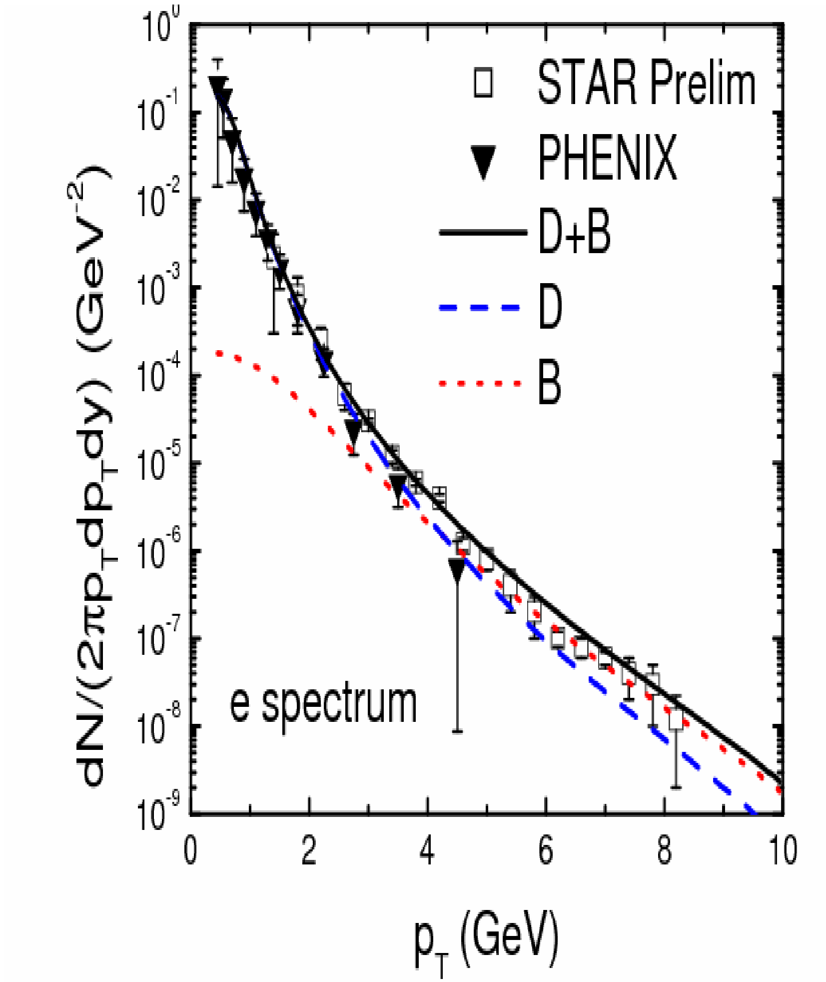
H

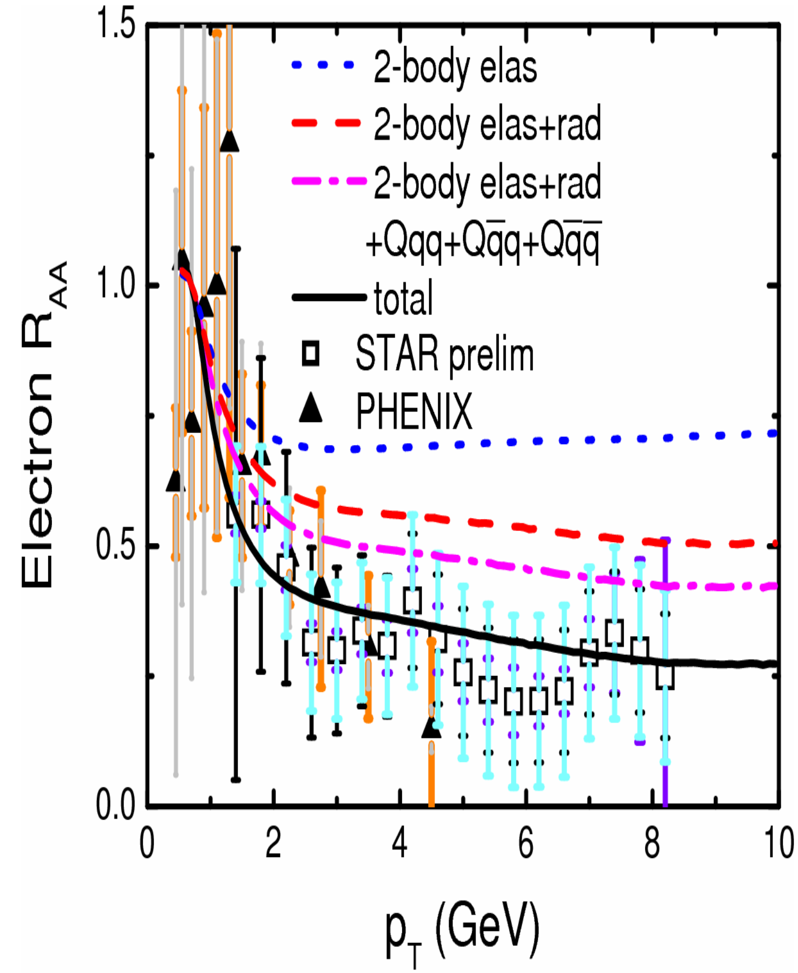
e

$$D(z)=\frac{1}{z[1-1/z-\varepsilon/(1-z)]^2}$$

$$\varepsilon_D = 0.02,\ \varepsilon_B = 0.002$$

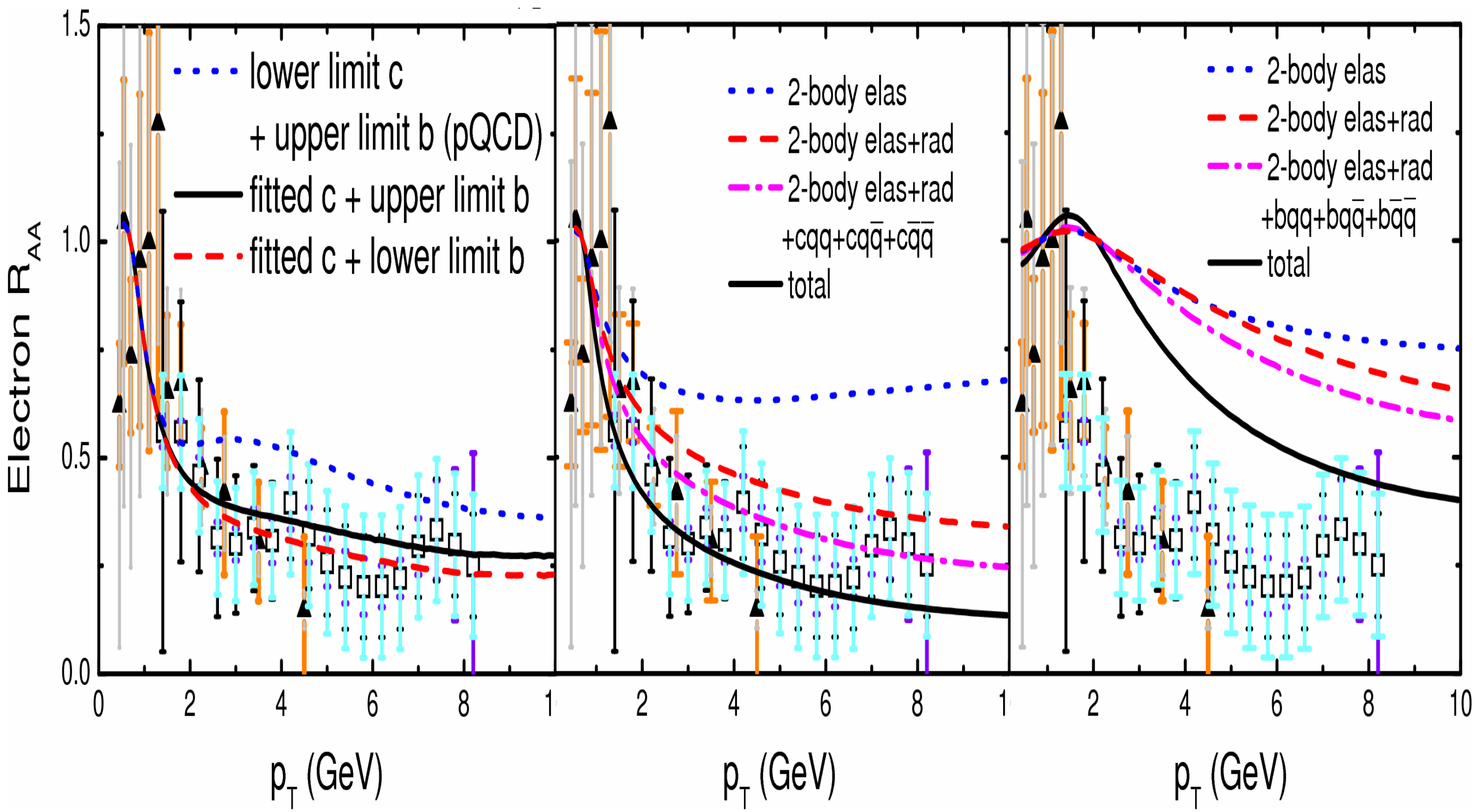
Spectrum and nuclear modification factor of electrons from heavy meson decay





Reasonable agreement with data from Au+Au @ 200A GeV after including heavy quark three-body scattering.

Other scenarios



Summary

- Heavy quark three-body scattering in QGP is important: comparable to both two-body elastic and radiative scattering for charm quarks; dominant for bottom quarks.

- Including three-body scattering helps to explain observed nuclear modification factor of electrons from heavy meson decays.

- More accurate evaluation of three-body scattering is required.

- Method for resumming multi-body scattering effect needs to be developed.

- Three-body scattering of gluon and light quark jets need to be studied.